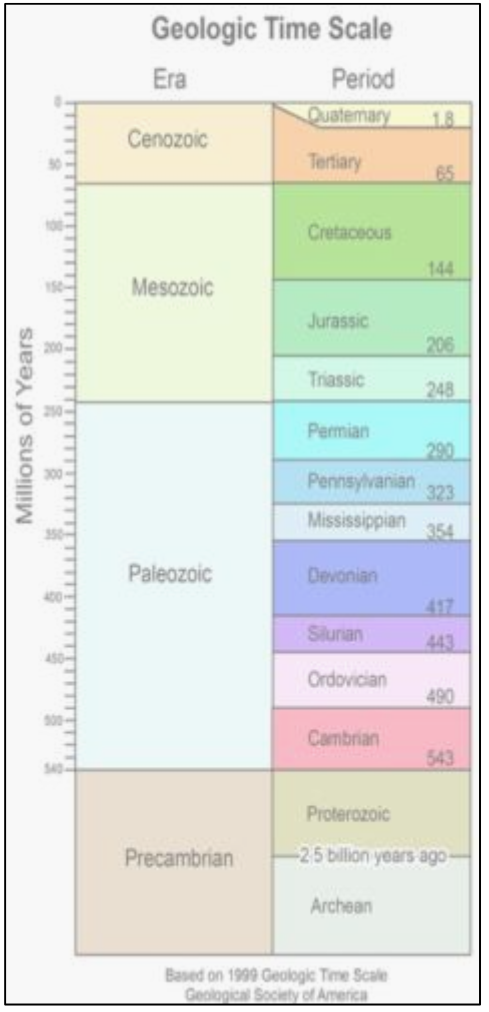
Agenda

The grand picture (Sustainability @ “Anthropocene”)

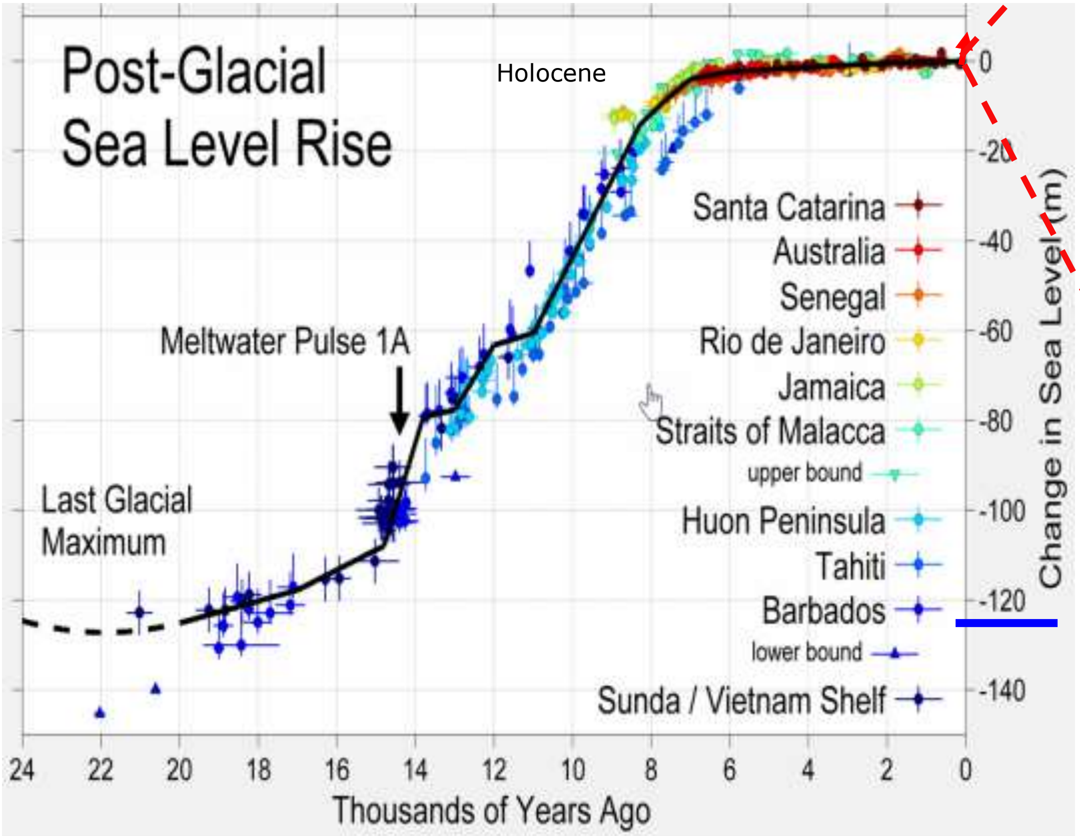
- Human habitat and resources.
- Sustainability of Human Activity & Life on Earth,
  Limit to growth, Club of Rome,
  Socio-economic/ecological network.
- Finite resources: arable land and water for food production, materials for fabrication & construction, fuels for machinery & transportation,
  Human eco-footprint, choices, and dilemmas,
- Energy utilization and environment,
  Energy consumption and human development
  Direct & external costs of energy use,
  Planetary climate, greenhouse effect.
- Stated (aspirational) and actual public policies, mitigation vs. adaptation to environmental & resource challenges.

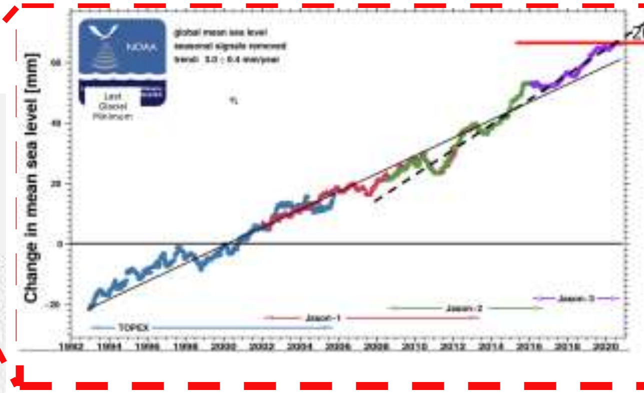


PLANETARY CLIMATE TRENDS AND CAUSATION

Ancient and Modern Recent Sea Level Trends

Parallel trends in ***T*** and sea-level rise





Adapted: https://commons.wikimedia.org/wiki/File:Post-Glacial_Sea_Level.png

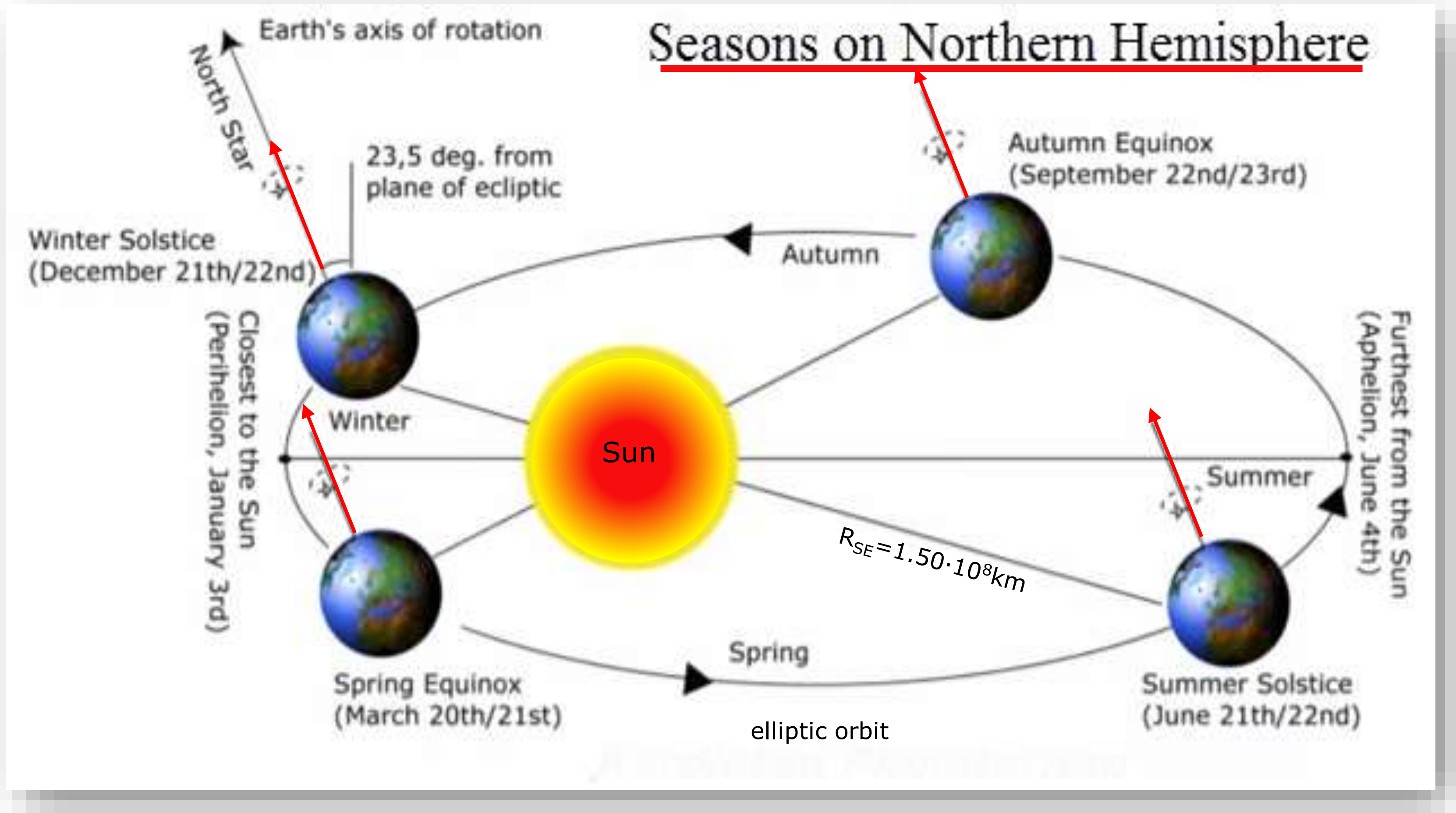
Sea levels since last glacial minimum.
Rise $\Delta H = +125$ m until 6000 BCE, then constant. (uncertainty $\Delta H = \pm 10$m)

2021: $\Delta H = +67$ mm since 1850, mean rate: **$\Delta H/\Delta\tau$ = (3.0± 0.4)mm/a**, slightly increasing.
Seasonal cycle ($\Delta H = \pm 7$mm) superimposed on general trend.
https://www.climate.gov/maps-data/dataset/global-mean-sea-level-graph

Q: Is there an explanation in terms of natural processes?
Are anthropogenic influences dominant for environmental/ climate trends?

Earth In Solar System

Energy transfer Sun → Planets via emission and absorption of **electromagnetic radiation**



Earth is a spinning gyro with an (approximately) **space-fixed orientation now towards North Star**.
Axis precesses and wobbles with 10ka-100ka periods.

Now: Axis misalignment with normal to plane of orbit (ecliptic) about Sun (23.5^0).

Climate "Forcing" Categories

Paleoclimatology achieved via study of Antarctic and Greenland ice cores, geological sedimentation, tree rings, coral reefs, records, …

Recent past via human records, oral history, temperature records

Now: various geophysical measurements on land and sea, e.g., remote satellite sensing.

Climate forcing := change imposed on Earth's surface energy balance/climate due to

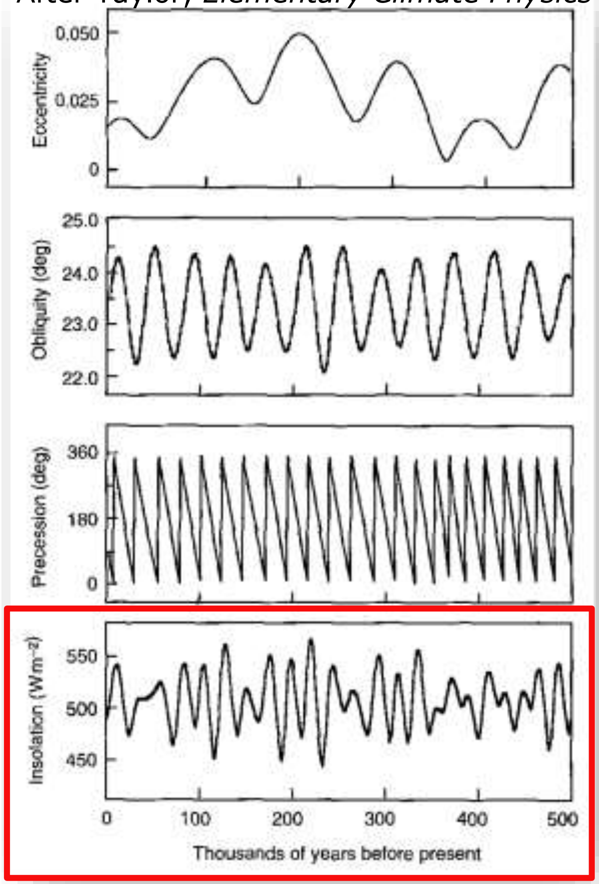
1) External causes (solar radiation influx):
   a) changes in Earth orbital eccentricity ($\Delta e \sim (0.01\text{-}0.2)\%$, $T_{ecc} \sim 110{,}000$ a),
   b) orbital precession ($T \sim 20{,}000$ a)
   c) obliquity ($\Delta\theta = \pm 1^0$, $T_{obl} \sim 40{,}000$ a) of rotational axis.
   d) Solar activity, sunspots ($T_{Sol} \sim (9\text{-}14)$ a)
   e) Impact of meteorites, asteroids.

2) Internal causes:
   a) Volcanic eruptions producing aerosols.
   b) Changes in oceanic currents.
   c) Changes in ice and cloud coverage (albedo).
   d) Human induced changes (emission of greenhouse gases, tropospheric aerosols, CFCs and HCFCs producing "ozone hole", deforestation).

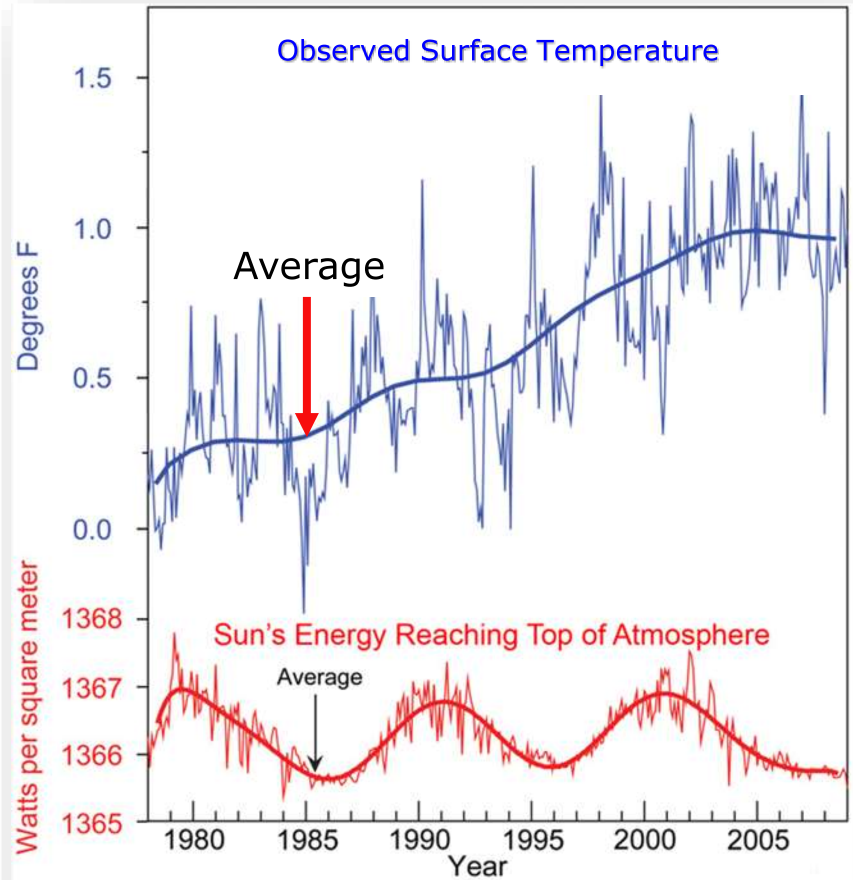
Correlate terrestrial observations with characteristic *t*-dependencies of potential causes

Elimination of Extra-Terrestrial Effects

After Taylor, *Elementary Climate Physics*



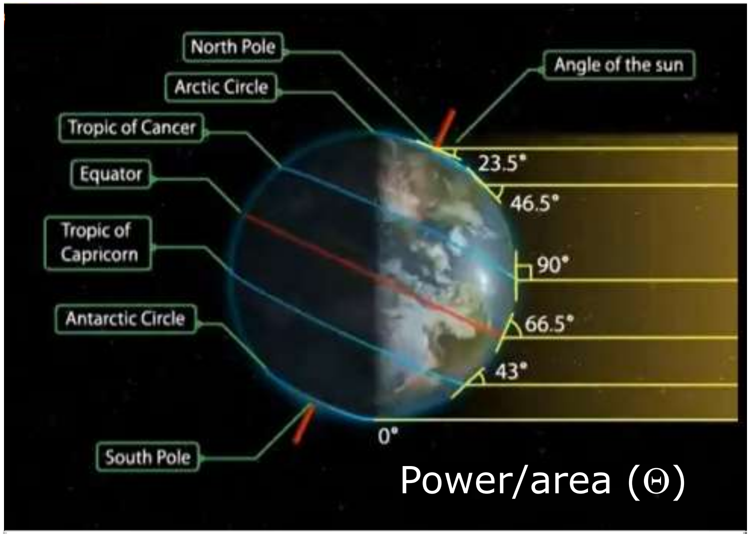
Modeling of influences of peculiarities of Earth planetary orbit and orientation (Milankovich cycles) on solar insolation gives somewhat irregular long-time pattern, approximately accurate (Ice Ages). Predicts no 11-year cycle.



The sun's energy received at the top of Earth's atmosphere has been measured by satellites since 1978. It has followed its natural 11-year cycle of small ups and downs, but with no net increase (bottom). Over the same period, global temperature has risen markedly (top).

Average temperature trend = superposition of insolation variation (11-year sunspot cycle) on steadily increasing temperature function $T(t)$ not seen in upper atmosphere.

"Black Body" Radiations: Sun and Earth



Solar radiation incidence during summer on northern hemisphere

Except for occasional flares (outbursts/mass ejections), the Sun emits **thermal radiation** like any "black body" at the same temperature *T*.

Planck's Radiation Law

"Radiance" for light of wave length λ emitted in random directions:

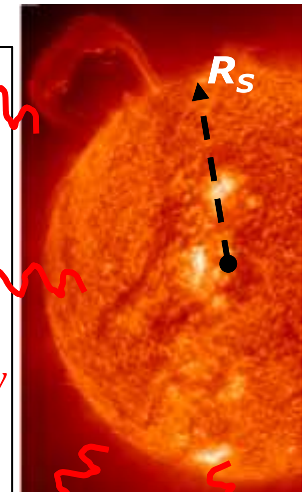
$$\boxed{R(\lambda,T)=\frac{2hc^2}{\lambda^5}\left[\frac{1}{e^{hc/\lambda kT}-1}\right]\left(\frac{W}{m^3\cdot sr}\right)}$$

Stephan – Boltzmann Radiation Law

Total power flux emitted

$$F=\int R(\lambda,T)\cdot d\lambda=\sigma\cdot T^4\ \left(W/m^2\right)$$

$$SB-constant:\sigma=5.670\cdot10^{-8}\ \left(W/K^4m^2\right)$$



R_S=6.96·10⁵km

$\pi R_S = 6.09\cdot10^{12}\,km^2$

Earth is also an approximately a "black body," but with a low temperature *T=255 K (-18^{0}C).*

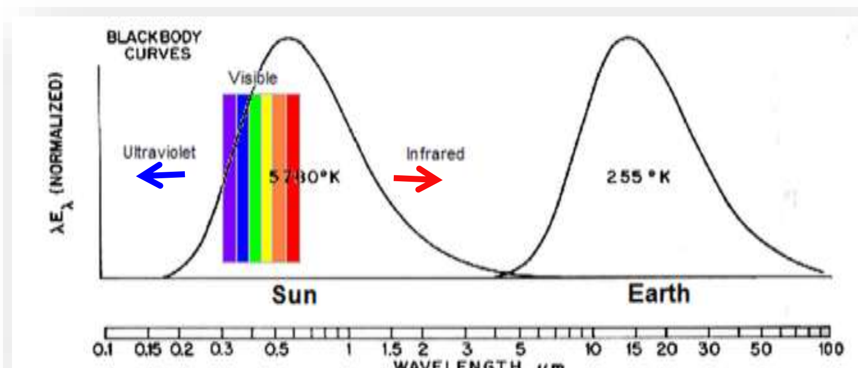
Role of atmosphere → raises ambient temperature ("good" greenhouse effect).

$h=6.625\cdot10^{-34}\ J\cdot s$ *Planck's constant*

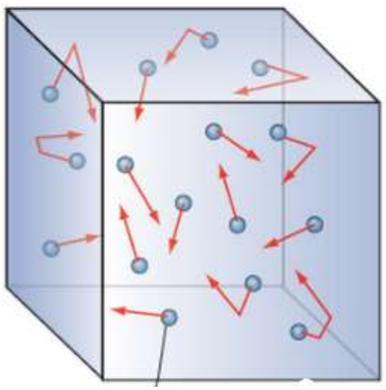
$k=1.3\cdot10^{-34}\ J\cdot s$ *Boltzmann's constant*

$c=2.998\cdot10^{8}\ m/s$ *speed of light*

sr = steradians = unit of angular acceptance $\Delta\Omega = Area/4\pi\cdot distance^2$

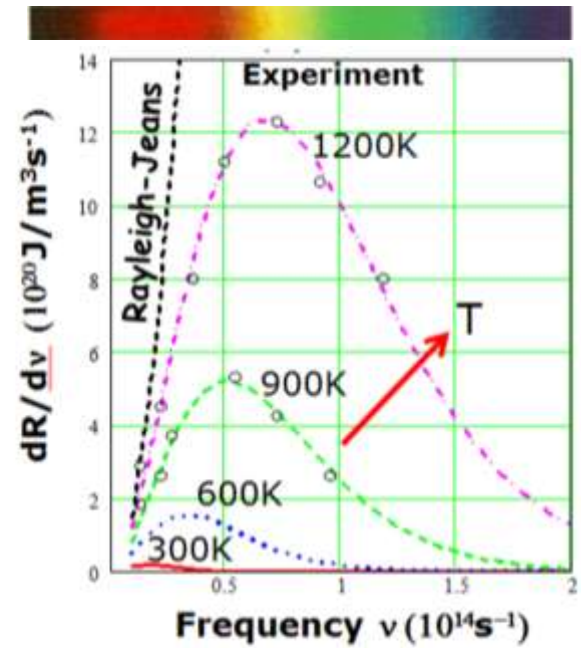


Thermal "Black Body" Radiation: Random Particle Motion



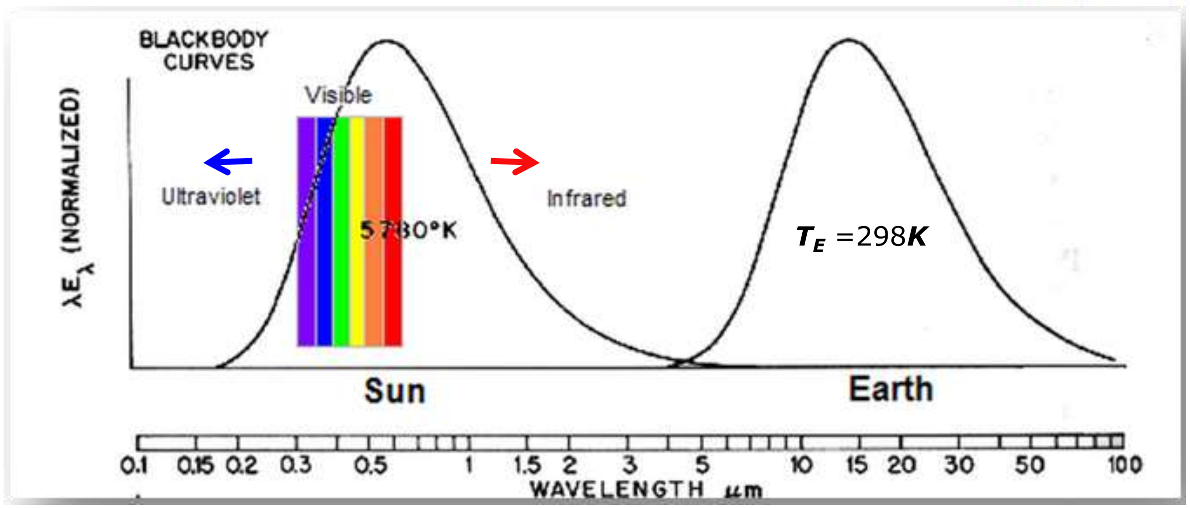
Any charged particles in random motion → continuous "thermal" kinetic energy spectrum.
→ Emit photons with continuous energy (ν, λ) spectrum

Equilibration & Relaxation →



Bare Earth is also approximately a "black body," but with a low temperature, equilibrium (estim.): T_E=298 K (25^{0}C).

Atmosphere =blanket → raises ambient T ("good" GHE)



Solar Insolation on Earth

Solar Constant S

$$Earth\ area\ A_E = 5.1\times10^8\ km^2$$

$$exposed\ to\ Sun = disk\ of\ area\ A_{R_{SE}} = \pi R_E^2 = \frac{1}{4}A_E$$

$$S\cdot A_{R_{SE}} = \sigma\cdot T_S^4\cdot\left(4\pi R_S^2\right)\cdot\left(\frac{A_{R_{SE}}}{4\pi R_{SE}^2}\right)$$

$$S = \sigma\cdot T_S^4\cdot\left(\frac{R_S^2}{R_{SE}^2}\right)\approx 1.370\,kW/m^2$$

$$Time\ averaged\ over\ spinning\ earth\ A_E = 4\,A_{R_{SE}}$$

$$S_{effective} = S/4 = 0.343\,kW/m^2$$

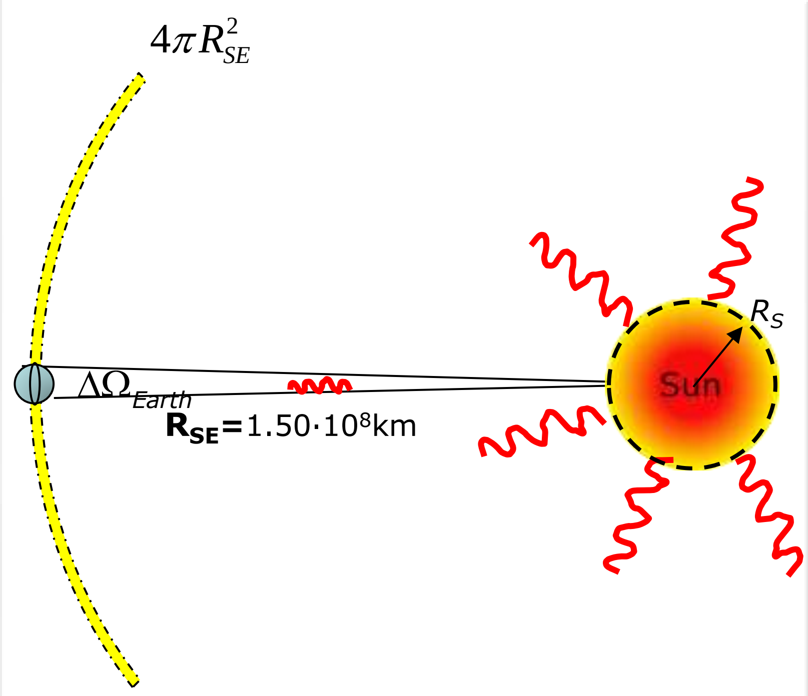
$$Albedo\ \alpha = reflectivity,\ \alpha_E\approx 0.3\ (expt.)$$

$$\rightarrow mean\ power\ absorbed\ by\ Earth's\ surface$$

$$S'_{eff} = (1-\alpha)\cdot S/4 = 0.240\,kW/m^2$$

$$T_E^{theo} = 255K\ (=-18^0C)\quad T_E^{actual} = 288K(+15^0C)$$

$(More\ sophisticated\ models\ for\ Earth\ energy\ balance\ are\ available)$



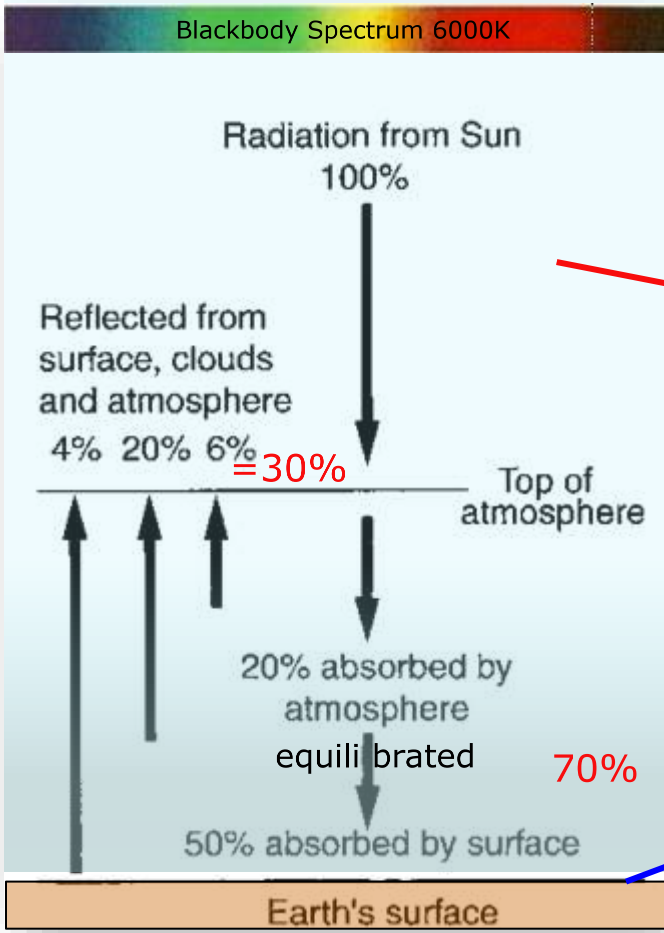
$$Solid\ Angle\ \Delta\Omega_{Earth} = A_{R_{SE}}/R_{SE}^2$$

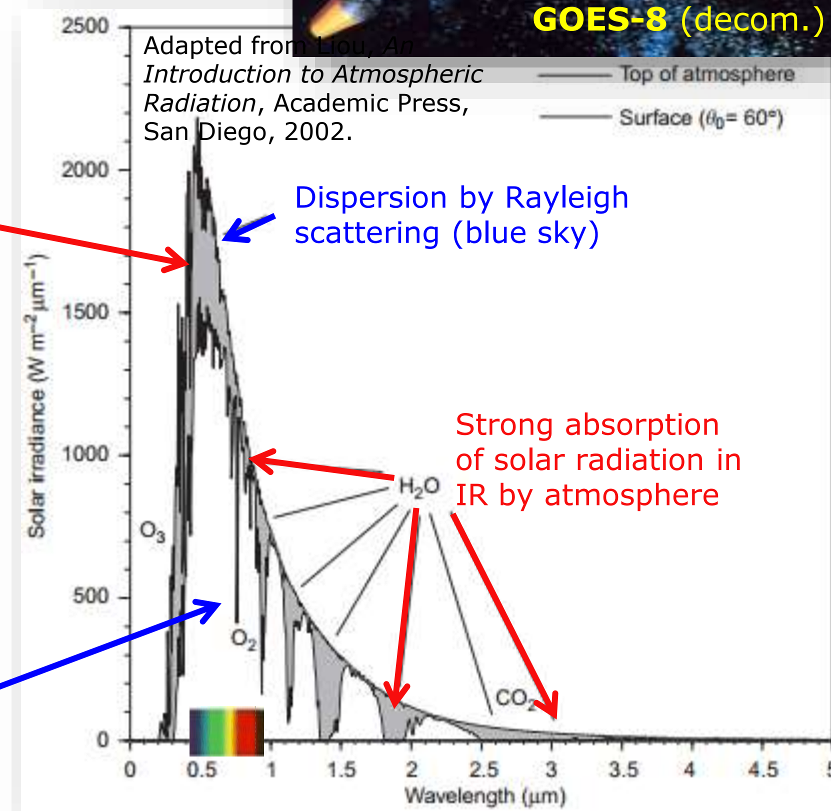
Effect of solar irradiation on Earth surface is non-cumulative, non-linear, possibly unstable.
System of several negative and positive feed-back effects.
Possible: Thermal equilibrium ?

Selective Filter Effect of Atmosphere

Absorption of solar radiation by the atmosphere is determined using spectroscopic satellite, aircraft, and surface data. See recent Atmospheric Radiation Measurement Enhanced Shortwave Experiment (ARESE)

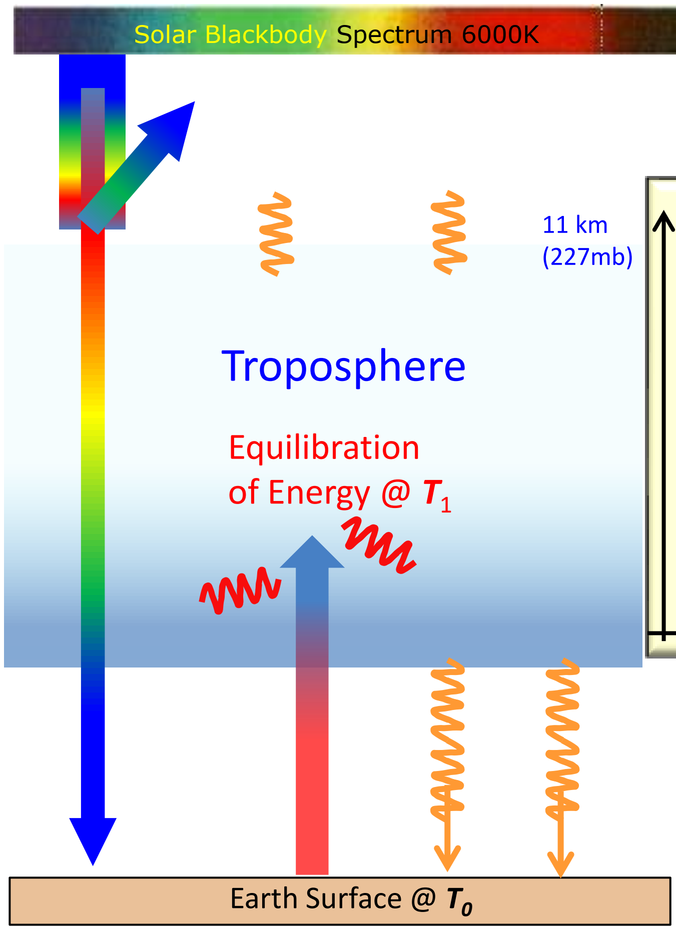
See, e.g., F. P. J. Valero et al., J. GEOPHYS. RES., 105, 4743 (2000)

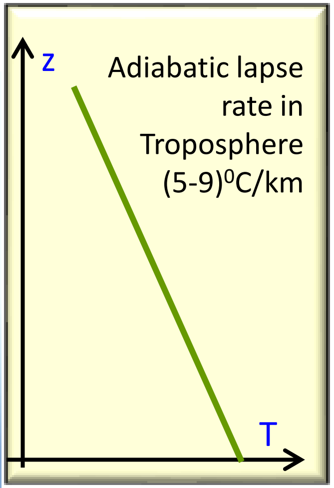




Scattered or absorbed radiation not available for warming Earth surface. → T_E < 255K !!???

Near-Surface Energy Equilibration (Clean Atmosphere)





Thermal equilibrium
$T_1 \approx T_0$

In actual calculations, atmosphere divided into layers, consider also clouds, dust, etc. Albedos of clouds, ocean, ice can be taken from measurement.

Greenhouse Effect

Solar radiation absorbed by the atmosphere is not totally lost to space.

Relaxation into IR thermal kinetic spectrum of atmospheric particles. Most of the atmosphere's energy content is radiated back to Earth surface.

In equilibrium *influx* = *outflux*

1) Earth surface + atmosphere receive Power density=S(1-a)/4.

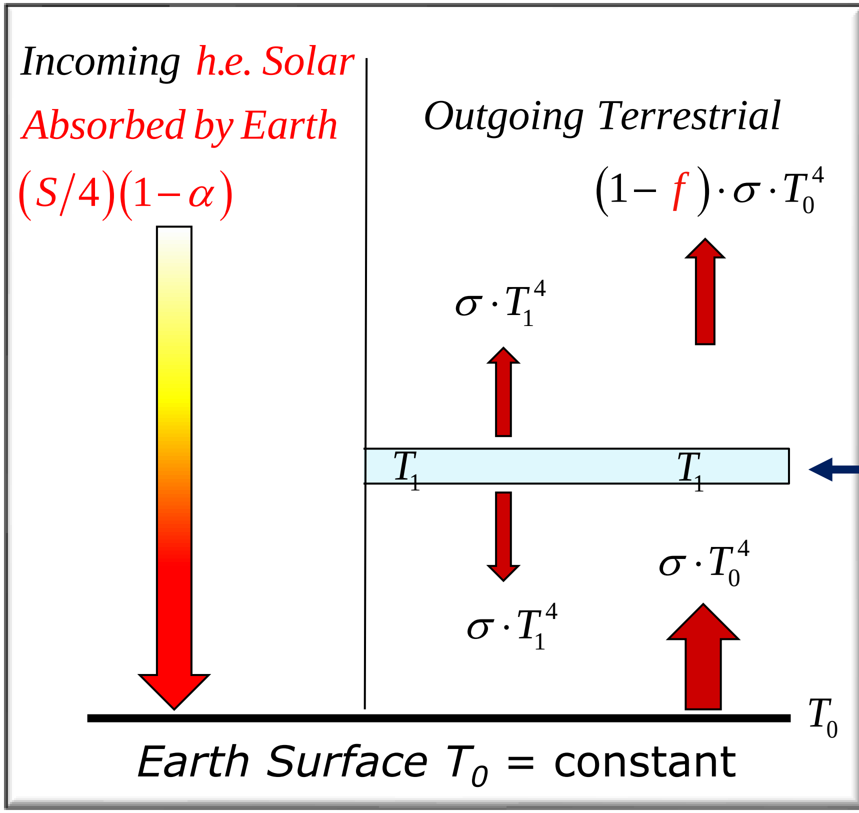
IR radiation from surface is absorbed by atmosphere, heating it up.

2) Atmosphere radiates P=S(1-a)/4 at low T back into space and at higher T toward surface, heating the surface in addition to direct insolation.

Solve numerically consistently in iteration. → T_E = 283 K (+10^{0}C)

See, e.g., F. P. J. Valero et al., J. GEOPHYS. RES., 105, 4743 (2000)

Simple Greenhouse Model



Approximations: Atmosphere is appr. transparent to incoming solar radiation. Earth surface absorbs part (1 - α) of it and emits absorbed energy as thermal radiation @ T_0. Fraction *f* of that rad. is absorbed by atmosphere layer, heating it to T_1. Remaining (1 - *f*) is lost to space.

$$\textit{Energy Content}\quad f\cdot\sigma\cdot T_0^4$$

$$f\cdot\sigma\cdot T_0^4 = 2\cdot\sigma\cdot T_1^4 \rightarrow T_1 = (f/2)^{1/4}\cdot T_0$$

Stationary state equilibrium requires

$$\textit{Absorbed} \equiv \textit{Radiated Energy (Power F)}$$

$$(S/4)(1-\alpha) \equiv (1-f)\cdot\sigma\cdot T_0^4 + (f/2)\cdot\sigma\cdot T_0^4$$

$$F_{out} = (1-f/2)\cdot\sigma\cdot T_0^4 \rightarrow \boxed{\Delta F_{retained} = (f/2)\cdot\sigma\cdot T_0^4}$$

GHG Effect

$$\rightarrow T_0 = \left[\frac{F_{in}}{F_{out}}\right]^{1/4} = \left[\frac{(S/4)(1-\alpha)}{\sigma\cdot(1-f/2)}\right]^{1/4}$$

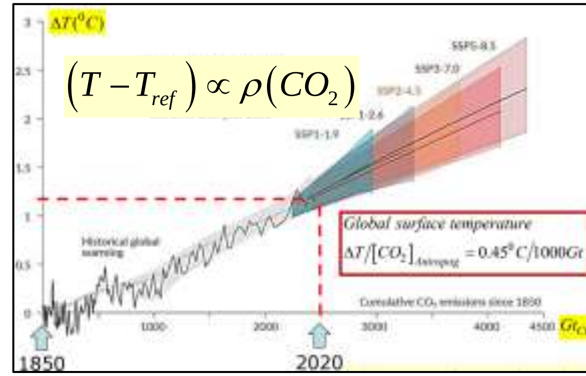
$$\textit{Observed}: T_0 = 288\,K \rightarrow f = 0.77$$

$$\rightarrow T_1 = 2^{-1/4}T_0 = 241\,K \;\; \textit{corresponds to } z = 7\,km$$

Improve model by accounting for altitude dependent, continuous absorption *f*(z).

Radiative Forcing Produces Linear Correlation T_0-$\rho(CO_2)$

Atmospheric Perturbations (adding GHG) produce changes in heat absorption $f \rightarrow f+\Delta f$ $\boxed{\Delta f \propto \Delta\rho_{CO_2}}$



→ ***Forcing = ΔF*** = change in *power* flux *outgoing from Earth surface (reflects surface T_0)*.

Check with simple GH model if: $\Delta T_0 = \lambda \cdot \Delta f$
disregard absorption by atmosphere

For a fixed T_0, perturbation Δf changes the emitted power flux by

$$\Delta F := \Delta F_{out} = \left[1-\left(f+\Delta f\right)/2\right]\cdot\sigma\cdot T_0^4 - \left[1-f/2\right]\cdot\sigma\cdot T_0^4 = \frac{-\Delta f}{2}\cdot\sigma\cdot T_0^4 \qquad \rightarrow \underline{\Delta F_{in} \propto +\Delta f}$$

$$T_0 = ??? \rightarrow \textit{Equilibration of the same absorbed solar flux}: T_0 \rightarrow T_0' = T_0 + \Delta T_0$$

Due to Δf

$$F = (S/4)(1-\alpha) = (1-f/2)\cdot\sigma\cdot T_0^4 \overset{!}{=} \left[1-\left(f+\Delta f\right)/2\right]\cdot\sigma\cdot\left[T_0+\Delta T_0\right]^4$$

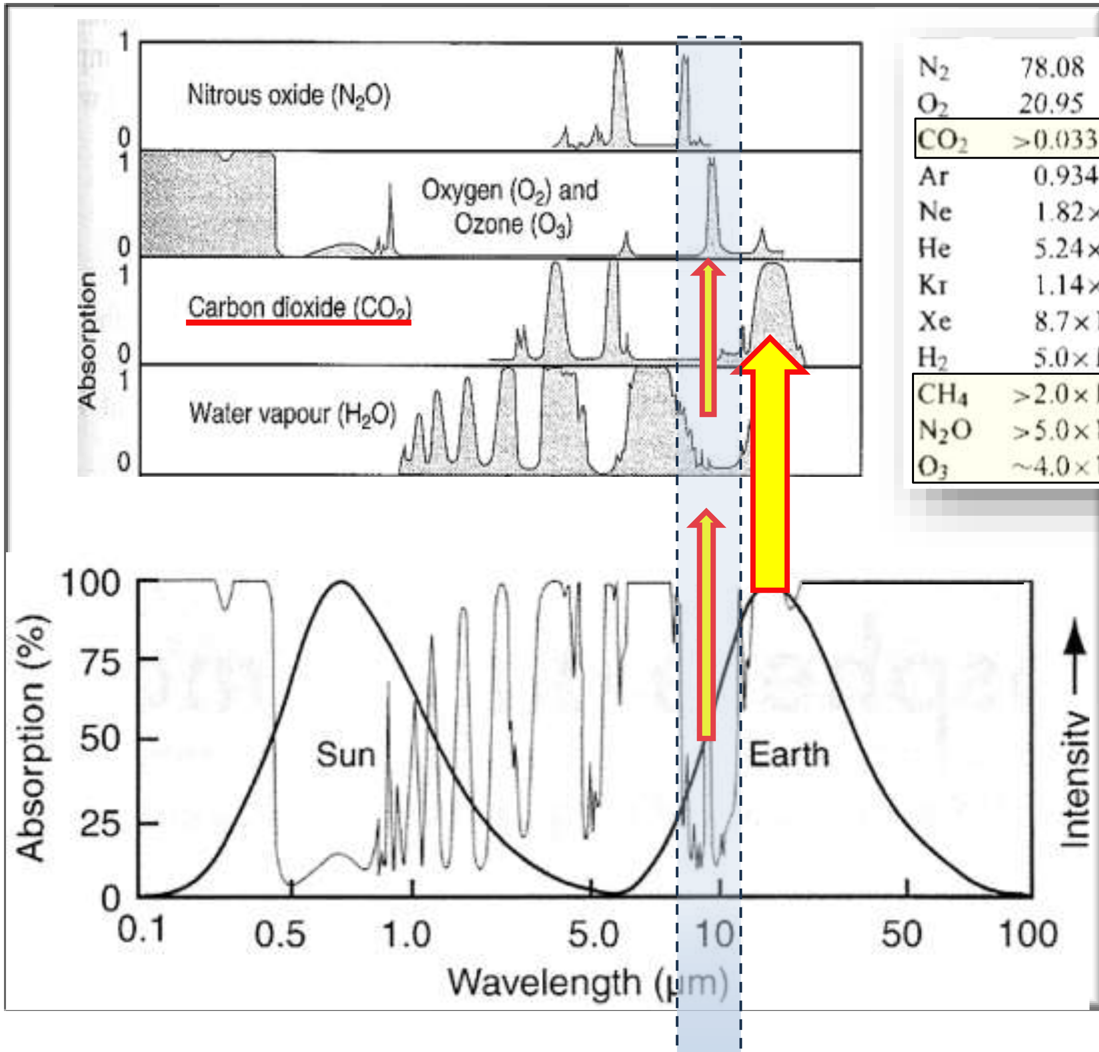
$$\left[T_0+\Delta T_0\right]^4 \approx T_0^4\cdot\left[1+\Delta T_0/T_0\right]^4 \approx T_0^4 + 4T_0^4\left(\Delta T_0/T_0\right) \qquad \textit{for } \Delta T_0/T_0 \ll 1$$

Linear in Δf

$$\rightarrow \Delta T_0 \approx \frac{T_0}{8\left(1-f/2\right)}\cdot\Delta f = \frac{1}{4\left(1-f/2\right)\sigma T_0^3}\cdot\Delta F =: \lambda\cdot\Delta F \qquad \Rightarrow \qquad \boxed{\Delta T_0 \propto \Delta f \propto \Delta\rho_{CO_2}}$$

Increasing GHG concentration → increases absorption of surface radiation
→ increases surface temperature T_0

Selective Absorption of Atmospheric GHG



N_2	78.08
O_2	20.95
CO_2	>0.033
Ar	0.934
Ne	1.82×10^{-3}
He	5.24×10^{-4}
Kr	1.14×10^{-4}
Xe	8.7×10^{-6}
H_2	5.0×10^{-5}
CH_4	$>2.0\times10^{-4}$
N_2O	$>5.0\times10^{-5}$
O_3	$\sim4.0\times10^{-6}$

Scattered radiation is not fully available for warming Earth surface. → T_E < 255K

Absorption of radiation in atmosphere → equilibrates → radiates back to space and to Earth surface.

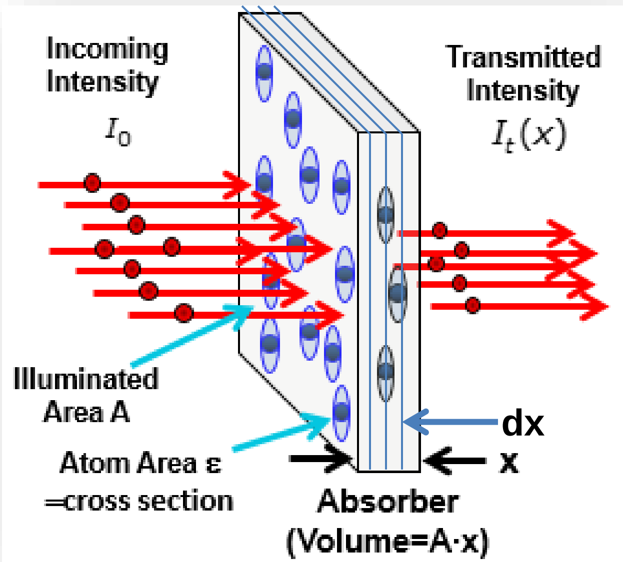
CO_2 absorbs efficiently @ maximum of the Earth' surface spectrum;

N_2O and CH_4 absorb in atmospheric escape hole for radiation.

GHG concentrations on the rise during the last century.

Adapted fro F.W. Taylor, *ECP*.

Absorption of *elm* Radiation: Beer-Lambert Law



$Incoming\ intensity\ I_0 = I(x=0)\ blocked\ by\ \varepsilon\ per\ atom$

$Intensity\ absorbed\ along\ path\ length\ \Delta x : -\Delta I = f \cdot I \cdot \Delta x$

.........(→ calculus)

$Probability\ (fraction)\ f\ for\ absorption\ of\ -dI$

$in\ the\ next\ slice\ of\ absorber\ dx :\ \underline{dP_{abs}(x) \propto dx}$

$$f = dP_{abs}(x) = \frac{-dI}{I(x)} = \mu \cdot dx \qquad (fraction\ of\ I\ abs.)$$

$$\frac{dI}{dx} = -\mu \cdot I(x) \quad \rightarrow DEq\ for\ power\ law$$

$Transmitted:\ \boxed{I_t = I(x) = I_0 \cdot e^{-\mu \cdot x}} \quad \mu := \rho_{particle} \cdot \varepsilon$

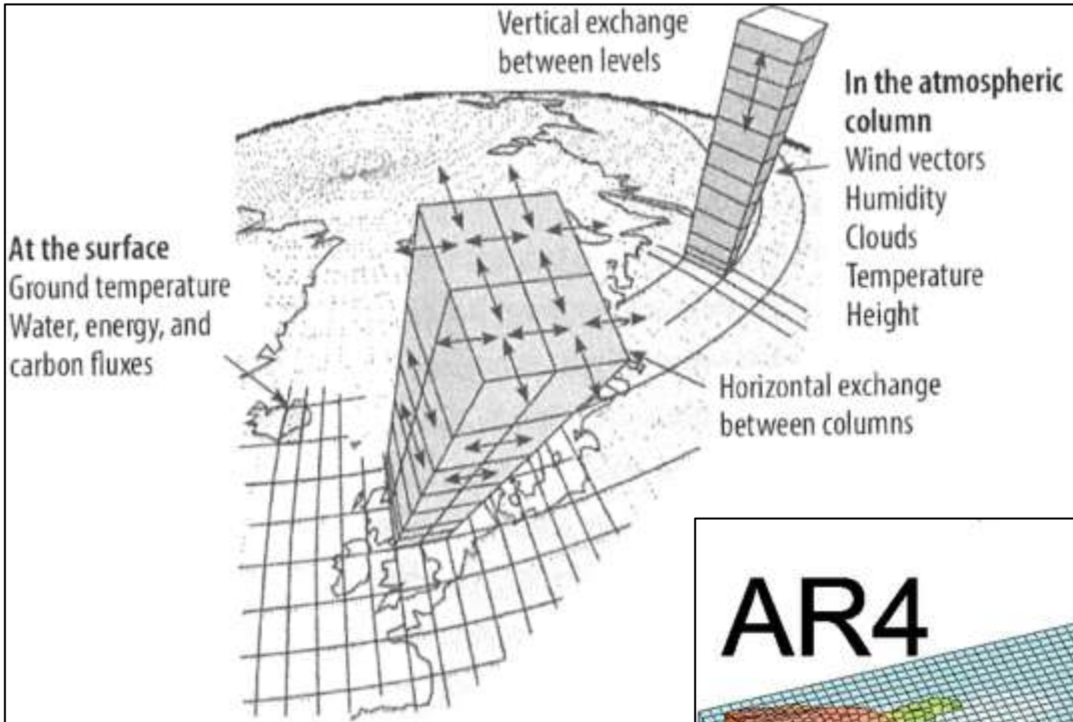
$Absorbed:\ \boxed{I_a = I_0 - I(x) = I_0\left(1 - e^{-\mu \cdot x}\right)}$

Can use base ***10*** instead of base ***e=2.718….*** Customary: use $\log_{10}$ instead of ***ℓn***.

$\rightarrow Absorbance: Log_{10}\left(\frac{I_0}{I_t}\right) = \mu \cdot x = \varepsilon \cdot x \cdot c$ Units of $\boldsymbol{\mu}$ and $\boldsymbol{\varepsilon}$ depend on unit of *c*.

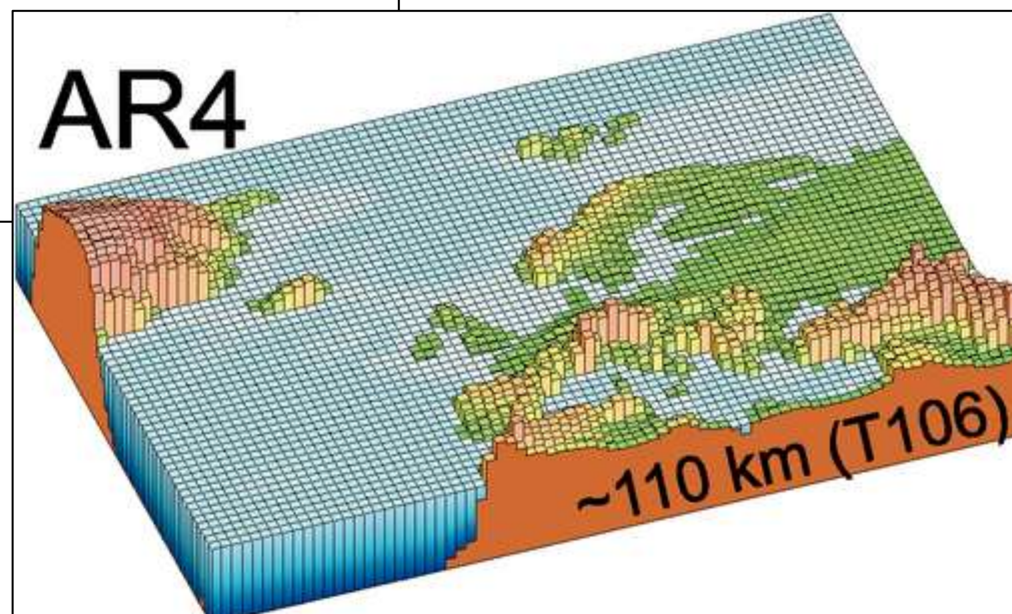
Specific for absorber material, depends on internal structure, electric dipole moment. Otherwise, μ ≠ 0 only for ionized ideal gas.

Climate Models: Geographic Resolution



S.E. Koonin, *Unsettled ?*(2021)

Improved spatial resolution of hydrodynamic simulation codes used for extensive IPCC climate models. Require days of Supercomputer power.



AR6 (2022): lateral resolution 25 km, vertical resolution many oceanic and atmospheric layers. Challenge: clouds.

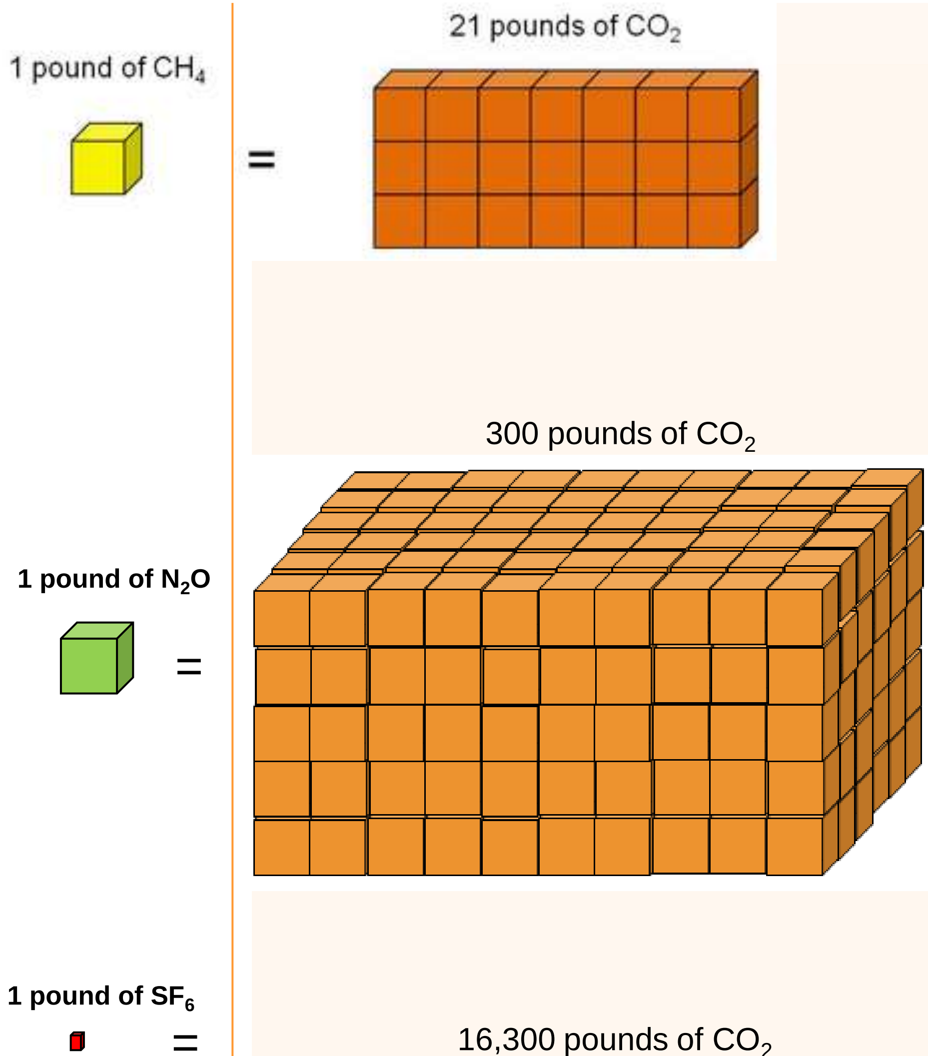
Global Warming Potentials: Data

Species	Chemical formula	Lifetime (years)	Global Warming Potential (Time Horizon)		
			20 years	100 years	500 years
CO_2	CO_2	variable §	1	1	1
Methane *	CH_4	12±3	56	21	6.5
Nitrous oxide	N_2O	120	280	310	170
HFC-23	CHF3	264	9100	11700	9800
HFC-32	CH2F2	5.6	2100	650	200
HFC-41	CH3F	3.7	490	150	45
HFC-43-10mee	C5H2F10	17.1	3000	1300	400
HFC-125	C2HF5	32.6	4600	2800	920
HFC-134	C2H2F4	10.6	2900	1000	310
HFC-134a	CH2FCF3	14.6	3400	1300	420
HFC-152a	C2H4F2	1.5	460	140	42
HFC-143	C2H3F3	3.8	1000	300	94
HFC-143a	C2H3F3	48.3	5000	3800	1400
HFC-227ea	C3HF7	36.5	4300	2900	950
HFC-236fa	C3H2F6	209	5100	6300	4700
HFC-245ca	C3H3F5	6.6	1800	560	170
Sulphur hexafluoride	SF6	3200	16300	23900	34900
Perfluoromethane	CF4	50000	4400	6500	10000
Perfluoroethane	C2F6	10000	6200	9200	14000
Perfluoropropane	C3F8	2600	4800	7000	10100
Perfluorobutane	C4F10	2600	4800	7000	10100
Perfluorocyclobutane	c-C4F8	3200	6000	8700	12700
Perfluoropentane	C5F12	4100	5100	7500	11000
Perfluorohexane	C6F14	3200	5000	7400	10700

United Nations
Framework Convention on Climate Change

http://unfccc.int/ghg_data/items/3825.php

Global Warming Potential (GWP)



Main factors:

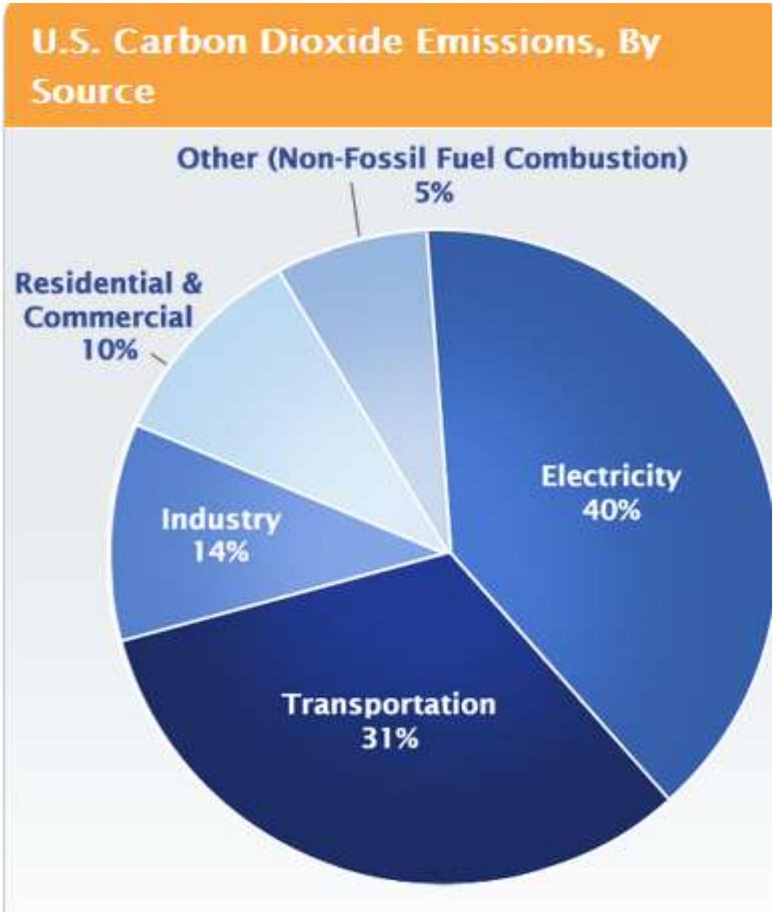
1) Effectiveness to trap heat (GWP#)
2) Abundance in atmosphere
3) Residence/lifetime in atmosphere

CO_2: GWP := 1 (reference).
Lifetime in Earth's atmosphere ~100 a.

CH_4: GWP = 21
Lifetime in Earth's atmosphere ~12 a.

N_2O: GWP = 300
Lifetime in Earth's atmosphere ~120 a.

US GHG Emission Sources (2010)



Note: All emission estimates from the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2010.*

Electricity (40% of total CO_2, 33% of GHG emission) via combustion of fossil fuels. Coal produces more CO_2 than oil or natural gas.

Transportation (31% of CO2 , 26% of GHG), via combustion of fossil fuels. This category includes transportation sources such as highway vehicles, air travel, marine transportation, and rail.

Industry (14% of CO2 , 20% of GHG) mostly via fossil fuel combustion. Some important processes also produce CO_2 via chemical reactions (not combustion).

Examples: production and consumption of mineral products (e.g., cement), production of metals (e.g., iron, steel, etc.), production of certain chemicals.

Indirect CO_2 production via use of electricity (e.g., aluminum, composites,…).

1990-2010: U.S. Trends relatively stable (app. 6 Gt CO_2/a) → contra Kyoto Protocol !!

W. Udo Schröder, 2024

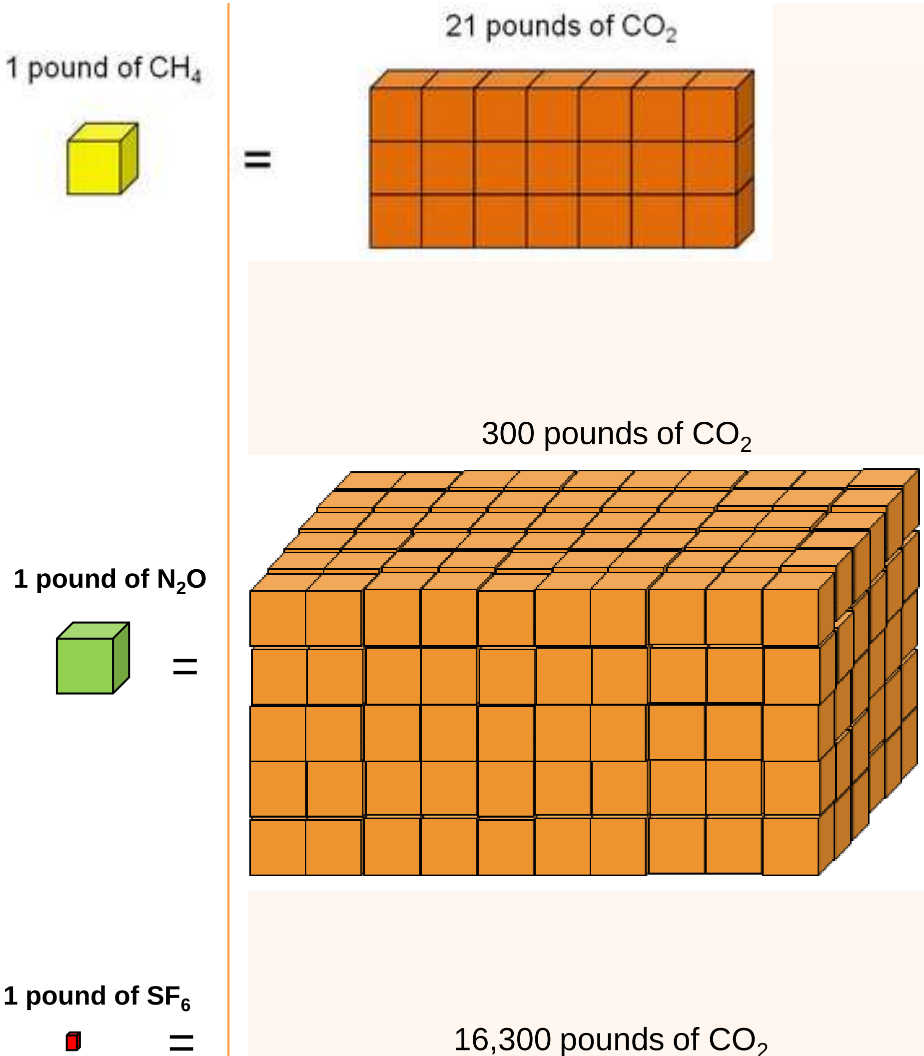
Global Warming Potentials: Data

Species	Chemical formula	Lifetime (years)	Global Warming Potential (Time Horizon)		
			20 years	100 years	500 years
CO_2	CO_2	variable §	1	1	1
Methane *	CH_4	12±3	56	21	6.5
Nitrous oxide	N_2O	120	280	310	170
HFC-23	CHF3	264	9100	11700	9800
HFC-32	CH2F2	5.6	2100	650	200
HFC-41	CH3F	3.7	490	150	45
HFC-43-10mee	C5H2F10	17.1	3000	1300	400
HFC-125	C2HF5	32.6	4600	2800	920
HFC-134	C2H2F4	10.6	2900	1000	310
HFC-134a	CH2FCF3	14.6	3400	1300	420
HFC-152a	C2H4F2	1.5	460	140	42
HFC-143	C2H3F3	3.8	1000	300	94
HFC-143a	C2H3F3	48.3	5000	3800	1400
HFC-227ea	C3HF7	36.5	4300	2900	950
HFC-236fa	C3H2F6	209	5100	6300	4700
HFC-245ca	C3H3F5	6.6	1800	560	170
Sulphur hexafluoride	SF6	3200	16300	23900	34900
Perfluoromethane	CF4	50000	4400	6500	10000
Perfluoroethane	C2F6	10000	6200	9200	14000
Perfluoropropane	C3F8	2600	4800	7000	10100
Perfluorobutane	C4F10	2600	4800	7000	10100
Perfluorocyclobutane	c-C4F8	3200	6000	8700	12700
Perfluoropentane	C5F12	4100	5100	7500	11000
Perfluorohexane	C6F14	3200	5000	7400	10700

United Nations Framework Convention on Climate Change

http://unfccc.int/ghg_data/items/3825.php

Global Warming Potential (GWP)



Main factors:

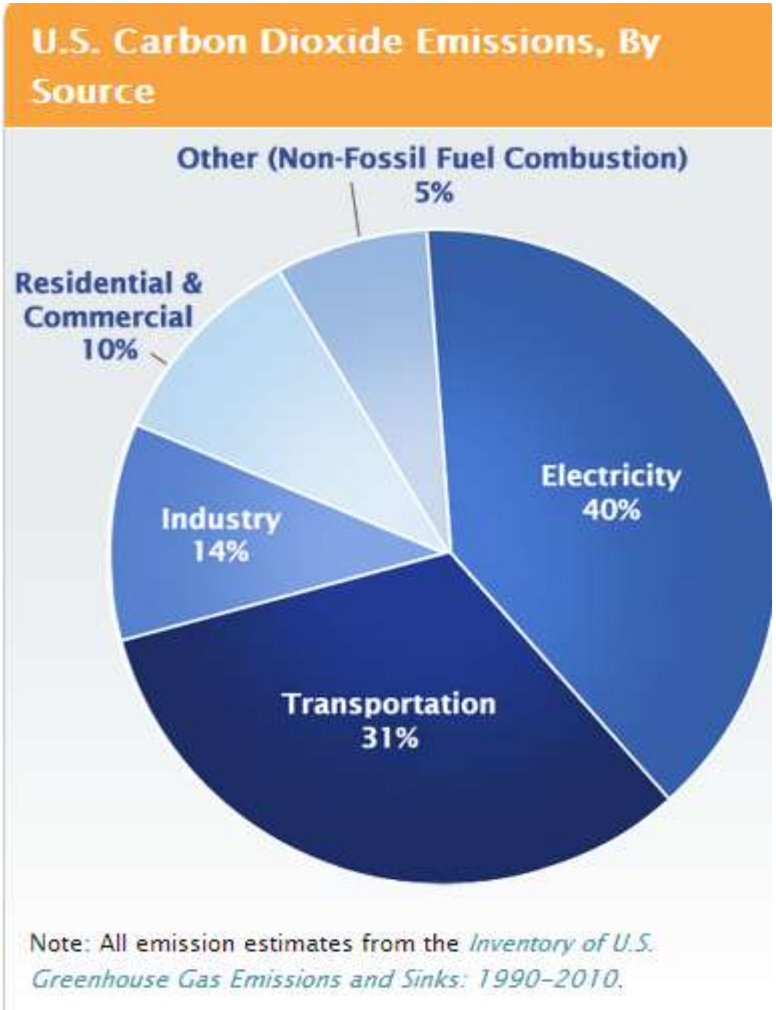
1) Effectiveness to trap heat (GWP#)
2) Abundance in atmosphere
3) Residence/lifetime in atmosphere

CO_2: GWP := 1 (reference).
Lifetime in Earth's atmosphere ~100 a.

CH_4: GWP = 21
Lifetime in Earth's atmosphere ~12 a.

N_2O: GWP = 300
Lifetime in Earth's atmosphere ~120 a.

US GHG Emission Sources (2010)



Electricity (40% of total CO_2, 33% of GHG emission) via combustion of fossil fuels. Coal produces more CO_2 than oil or natural gas.

Transportation (31% of CO2 , 26% of GHG), via combustion of fossil fuels. This category includes transportation sources such as highway vehicles, air travel, marine transportation, and rail.

Industry (14% of CO2 , 20% of GHG) mostly via fossil fuel combustion. Some important processes also produce CO_2 via chemical reactions (not combustion).

Examples: production and consumption of mineral products (e.g., cement), production of metals (e.g., iron, steel, etc.), production of certain chemicals.

Indirect CO_2 production via use of electricity (e.g., aluminum, composites,…).

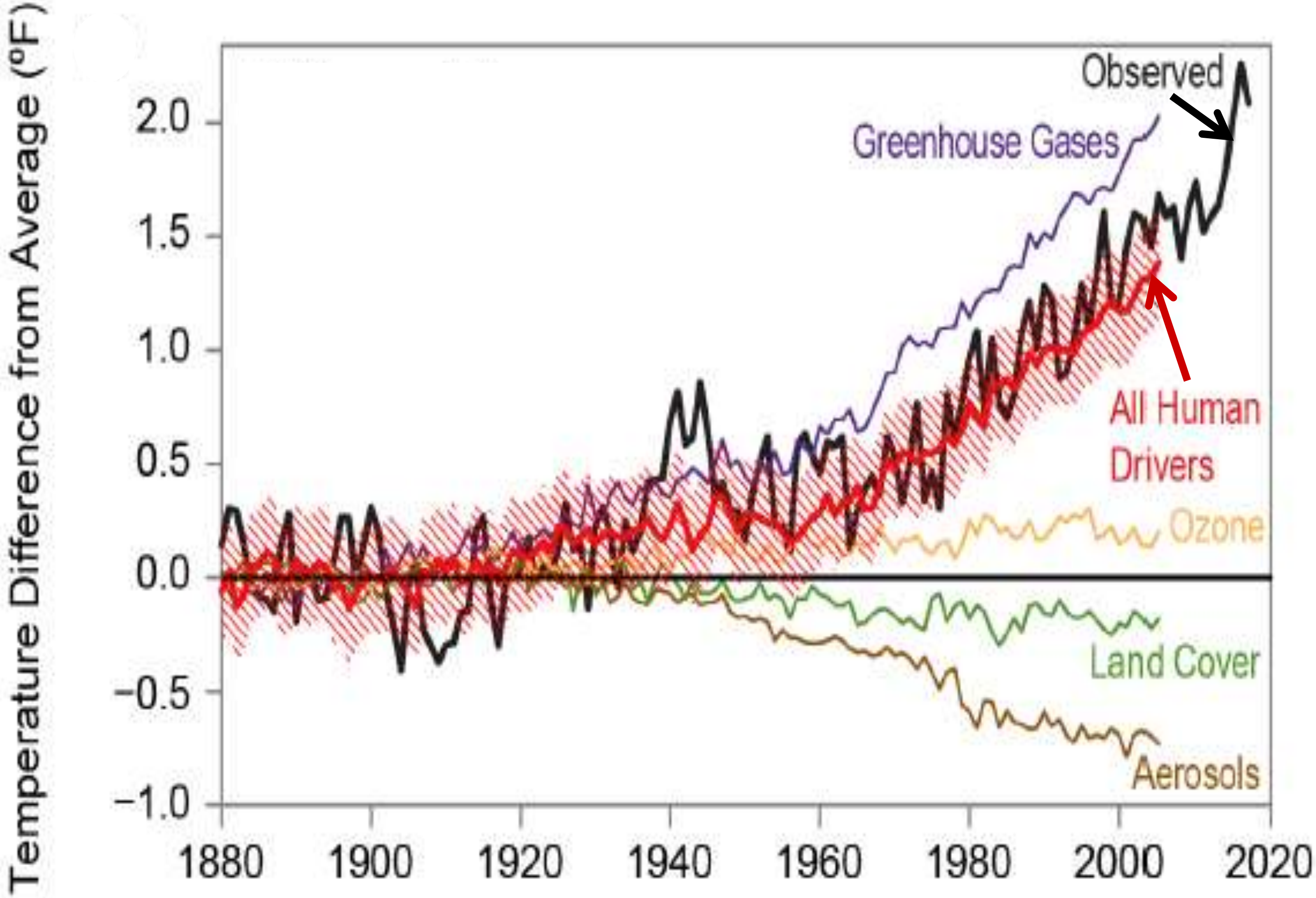
1990-2010: U.S. Trends relatively stable (app. 6 Gt CO_2/a) → contra Kyoto Protocol !!

Anthropogenic Influences: Global Climate

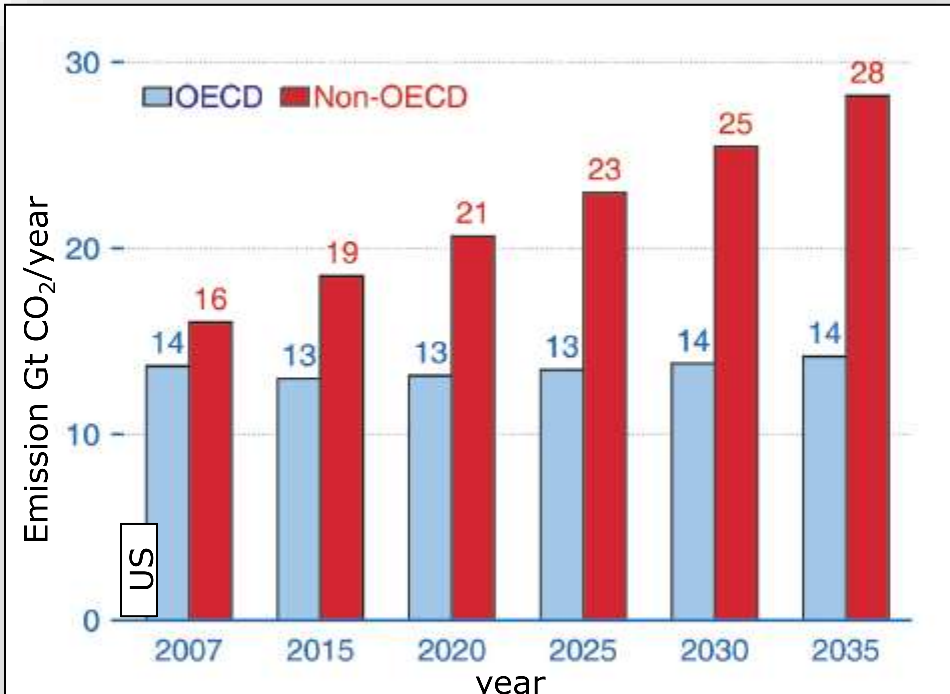
Many correlations exist between human caused pollution and global climate parameters: To what extent are there causal relationships ?

→ Quantitative agreement between observation and robust physical models

→ Absence of plausible competing scenarios



Projections for CO_2 Emissions



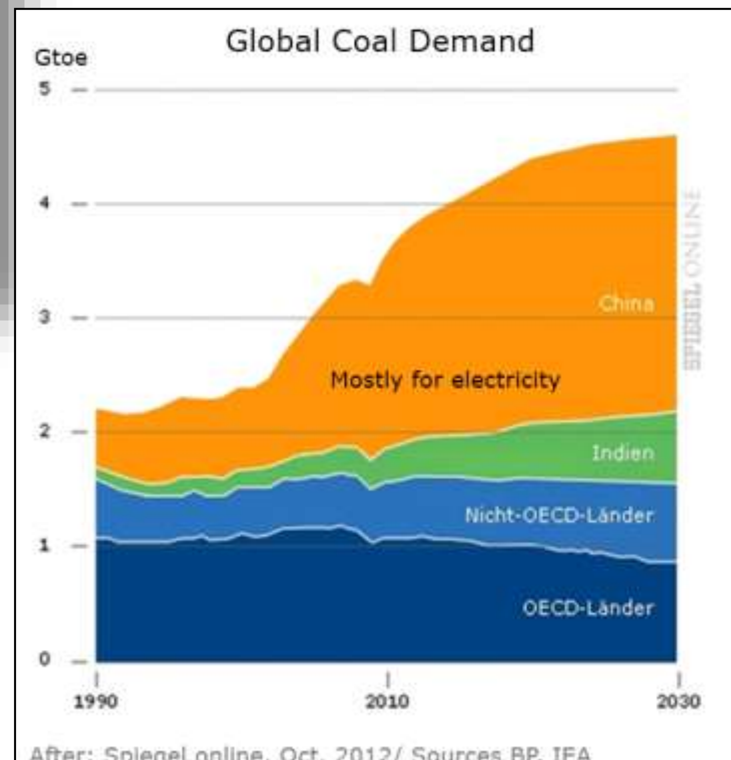
Energy Information Administration / International Energy Outlook. 2010

World energy-related CO2 emission projections (in billion metric tons CO_2), by OECD (Organization for Economic Cooperation and Development) and non-OECD countries over the period 2007-2035.

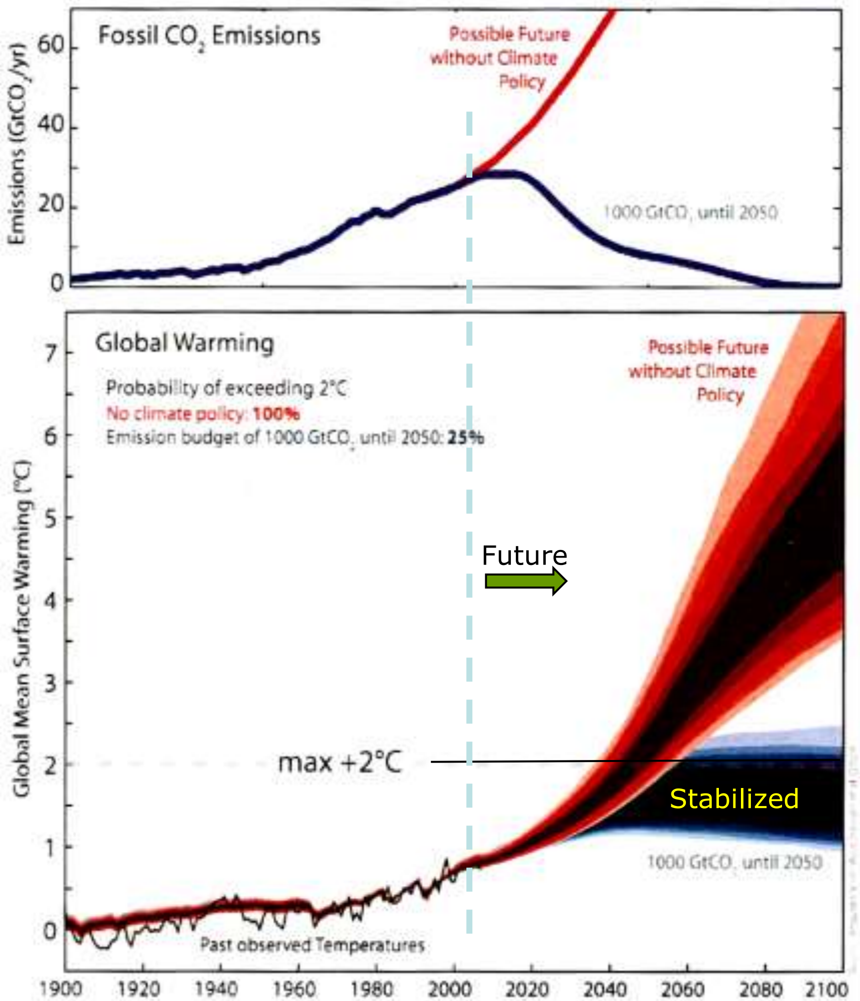
Non-OECD countries include developing, newly industrialized, Eastern European plus former Soviet countries. http://www.oecd.org/countrieslist/.

US (5% world population) produce 20% of global CO_2 emissions.

1 ton of oil equivalent (toe) = 42 GJ =energy released by burning 1 ton of crude oil.



Possible Climate Futures



Correlated with scenarios of constant, decreased or increased emissions of greenhouse gases.

Changing climate → changes in frequency, intensity, spatial extent, duration, timing of extreme weather and climate events, even produces unprecedented extreme weather and climate events. (NAS report).

Examples: Extensive heat waves and droughts, super-storms/hurricanes, extreme downpours, flash flooding, coastal flooding due to rising sea levels, atmospheric rain channels, troughs,…. Global: stopping the Gulf Stream.

$\Delta T \leq 2^0C$ until 2050 are relatively well manageable.

Larger temperature increases (4^0-6^0) are likely catastrophic.

By themselves, anecdotal (individual) weather events do not make a case for climate change. → Need systematic statistics over extended period to discover abnormalities and an understanding within a comprehensive overall picture (model of Earth).

National Climate Assessment and Development Advisory Committee

Summary Findings (2017, edited). Projections → 2100, Different polit. scenarios:

1) Global climate is changing, apparent in a wide range of observations. The climate change of the past 150 years is due largely to human activities (burning of fossil fuels).

2) Extreme weather and climate events have increased in recent decades; evidence is mounting for human activities as dominant cause (More recently "high confidence"_).

3) Human-induced part of climate change will accelerate significantly if emissions of heat-trapping gases continue to increase.

4) Impacts of climate change, evident in many sectors, become increasingly challenging.

5) Threats to human health and well-being from extreme weather events, wildfire, dangerous air quality, diseases transmitted by insects, food, and water, and threats to mental health.

6) Infrastructure is adversely affected by climate change: sea level rise, storm surge, heavy downpours, extreme heat.

7) Lower reliability of water supplies, affecting ecosystems and livelihoods in many regions: US Southwest, Great Plains, Southeast, Caribbean and Pacific islands, including the state of Hawaii.

8) Adverse impacts to crops and livestock over the next 100 years, increasing disruptions from extreme heat, drought, and heavy downpours.

9) Natural ecosystems directly affected, changes in biodiversity and location of species.

10) Life in the oceans is changing as ocean waters become warmer and more acidic.

11) Planning for adaptation (address and prepare for impacts) and mitigation (reduce emissions) is increasing, but progress with implementation is limited.

→ 12) Large-scale human migration

End: Global Climate